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8. SYNTHESIS AND CONCLUSIONS

The results of this dissertation show the modelling of indirect economic effects of floods, as well as additional insights into the economy-wide consequences of large-scale floods on both a regional and sectoral level. The research presented in this dissertation explores new methods by combining conventional risk modelling techniques with macroeconomic modelling approaches. One of the key novelties is the explicit incorporation of spatial and temporal dimensions within these new methodological approaches.

The main objective of this thesis is to explore to what extent we can incorporate the (socio) economic consequences in flood risk assessment modelling and how this may improve flood risk management strategies to anticipate future changes.

The main findings of the previous chapters are as follows:

1. In terms of risk, direct losses remain more substantial relative to indirect economic losses. The results indicate that the indirect/direct ratios range from 0.27 for continental studies to 0.68 for local studies. Nonetheless, in the instances of large-scale low-probability events, the indirect losses outweigh the direct losses.
2. For local studies, the results highlight large differences in the influence of model parameters between high-probability and low-probability floods. The speed of economic recovery after a flood event, for instance, largely influences economic damage for high-probability floods, whereas nearby potential substitution possibilities to a large extent determine the amount of indirect losses for low-probability floods.
3. The temporal dimension proves to be a large driver of indirect losses for studies on all scales. Both the recovery path and its duration largely determine the outcome of all models that are applied in this dissertation. For instance, the losses modelled through the use of a concave (quickest) recovery path can be more than six times lower in comparison to the convex (slowest) recovery path.
4. The explicit incorporation of the spatial dimension in disaster impact models, either via incorporating flood maps to improve the ‘disruption’ or via multiregional

modelling, substantially improves the outcomes compared to a model of the losses for only a single region. Besides, the multiregional effects show interesting new insights in the cascading effects to other regions, such as the additional trade flows that occur and the capacity of other regions to take over the production of an affected region.

5. Large differences exist between traditional IO models and the outcomes of more flexible economic models, such as hybrid IO- and CGE models applied in this dissertation (up to six times higher). These differences are largely driven by the linear structure assumed in traditional IO modelling, in contrast to the non-linear approach in the more flexible models applied in this dissertation.

6. The use of economic modelling tools in flood risk assessments prove to be useful to measure the effect of soft adaptation measures, such as the stimulation of the recovery speed in post-disaster recovery, or additionally, to make economic sectors more climate robust by diminishing the potential supply bottlenecks in the aftermath of the disaster. Both improvements to post-disaster recovery and the reduction of bottlenecks can respectively result in a risk reduction of up to 40%.

7. As slow recovery paths (linear and convex) are a large driver of indirect losses, an innovative adaptation strategy is to improve the recovery process through the removal of post-disaster production bottlenecks (e.g. under capacity of construction sector in the disaster aftermath), and to reduce the time to initiate this process. The results indicate that the indirect risk for the entirety of Europe can be reduced by 22% and 35% through increased post-disaster production speed.

8. Indirect effects on the household scale were analysed for the City of Rotterdam. It appears that the share of the population vulnerable to flooding that belongs to a relative lower class (low income, low education levels), is twice as large as the number of higher class people in flood-prone areas (16% versus 8%), respectively. Moreover, the share of the population that is highly vulnerable to flooding is almost 20 percent in areas that are not embanked, in comparison to only six percent in embanked areas. The latter implies that the most vulnerable people live in the areas most exposed to flooding.

The remainder of this final chapter summarizes the main findings regarding the research questions as stated in Section 1.3, discusses their impacts for flood risk management and provides recommendations for future research.

8.1. DISASTER IMPACT MODELS

This dissertation explores several modelling techniques to assess the indirect economic effects from flooding. This chapter extends the explored models to satisfy the characteristics that a disaster impact model is required to have in order to ‘properly’ assess these economic effects. These extensions are (1) the incorporation of a temporal dimension to capture the reconstruction period and (2) the spatial dimension to (i) explicitly incorporate inundation maps to define the economic disruption and (ii) to capture the spill over effects to other regions, both positive and negative.

In this context, two different methodologies and their strengths and weaknesses are discussed: Input-Output (IO) and Computable General Equilibrium (CGE) models. IO models offer simplicity, transparency, and their high level of detail on sector and regional inter-linkages lend these types of models to be powerful tools in disaster impact analysis. Relative to IO models, CGE models add more detail regarding the economic behaviour of agents, including reactions to price changes. Although IO and CGE models are based on rather different assumptions and are viewed as competing modelling traditions, they are in fact highly complementary in disaster impact analysis.

This dissertation explores and incorporates the temporal dimension in different models. Chapter 3 proposes a single-region hybrid IO model, which creates a dynamic model of total economic losses from a flood event to a full economic recovery. It explicitly models the reconstruction period after a flood event, and the results show that variation in the duration of the reconstruction period can substantially alter the outcomes (up to a factor 4 variation between lower and higher-bound estimates). To explore why the outcomes can vary, this research conducts an extensive sensitivity analysis to identify the parameters that are highly sensitive to model outcomes. The uncertainty and sensitivity analyses indicate a large variety in parameter values that renders the model outcome extremely sensitive (upper-bound estimates are up to

seven times higher than lower-bound estimates). Interestingly, large differences in parameter influence are found between high-probability and low-probability floods. For instance, the speed of labour recovery is of high influence for impacts from high-probability floods, whereas the assumed heterogeneity to a great extent determines the amount of indirect losses for low-probability floods. The heterogeneity of the economy is a measure of the diversity of the regional economy. More specifically, in a homogenous economy with similar industries, it is assumed to be easier to substitute products in comparison to a diverse economy with many different type of industries.

All chapters demonstrate that the selection of the recovery path and the duration of the reconstruction period largely determine the final indirect loss estimates. In the methods that Chapters 5 and 6 apply, the shape of the reconstruction curve is varied into a concave, linear and convex recovery curve (in addition to variation in the duration of recovery) (see Figure 6.2). The results show that the indirect losses determined with the use of a concave ('quickest') recovery curve can be more than six times lower compared to the convex ('slowest') recovery curve. However, besides the reconstruction time and the type of recovery path, the consideration of the reconstruction demand, defined as the additional demand to the construction sector for recovery, actually dampens losses as it provides a boost to the construction sector. Chapter 6 highlights that in the case that the reconstruction demand is not included in the model, the losses are not only up twice as high, but also vary significantly more between the several recovery curves within one flood scenario. The difference can be attributed to the increase in production (and thus increase in value added) due to the increased reconstruction demand from the affected sectors towards the construction sector.

Chapters 4, 5 and 6 take the spatial dimension into account in the modelling framework through their multiregional modelling approach. This modelling is done on both a national and international level. In Chapter 4, a recursive dynamic multiregional supply-use model is presented (in the chapter abbreviated as the MRIA model), which combines linear programming and input-output modelling techniques to assess the indirect economic consequences of a natural disaster on a pan-European scale. The MRIA model considers production technologies and allows for supply-side constraints. Results show that most of the neighbouring regions gain from the flood due to increased demand for reconstruction and production capacity

constraints in the affected region (gains can be as large as a few percentage points of gross regional product). Regions located further away or neighbouring regions that do not have a direct export link to the affected region mostly suffer small losses. These losses are due to the costs of increased inefficiencies in the production process that all the (indirectly) consuming regions.

In Chapter 6, two (hybrid) IO models and one CGE model are compared through an analysis of the potential different outcomes of two flood events in Italy. Only a few prior studies have compared disaster impacts of different model types in a systematic way and for the same geographical area, through the use of similar input data. The model applied in Chapter 3 serves as one of the two hybrid IO models, but is now extended to a multiregional model and altered to account for different recovery paths. The second hybrid IO model is the MRIA-model presented in Chapter 4. The CGE model is a regionally calibrated version of a global CGE model. Comparative results indicate that the difference in estimated total (national) economic losses for Italy and the regional distribution of those losses vary considerably between the three models. The modelling outcomes of the ARIO model are two to six times higher than the outcomes of the MRIA model and the regionally calibrated CGE model, depending on the chosen recovery path. The main reason for this difference is the linear structure assumed in the ARIO model. Due to the linear characteristics of the model, all other (non-affected) regions are negatively affected as a result of the disaster. Chapter 6 argues that this negative effect for all other regions is not realistic, and therefore, it is suggested that multiregional disaster impact studies apply more flexible economic models such as the MRIA or IEES model. It is important to note, however, that the indirect losses to the affected area are similar in all multiregional models. Finally, total economic impact, which is comprised of all Italian regions, is negative in all models.

The variety of economic models presented in this dissertation show that both IO and CGE models are capable of modelling the indirect economic effects of a disaster, albeit with slight modifications that lead them to be more specifically applicable for the purpose of studies. With the possibility to further extending and develop these models, it is expected that IO and CGE models are likely to remain among the most important tools used for disaster impact analysis at least in the near future.

8.2. INTEGRATION OF INDIRECT EFFECTS WITHIN CONVENTIONAL FLOOD RISK ASSESSMENTS

As already stated in Chapter 1, the assessment of the direct losses is mainly the domain of the engineering community, whereas the assessment of indirect losses is within the domain of the economic community. In this dissertation, I demonstrate how to close this gap, through the integration of the direct and indirect modelling approaches.

Chapter 3 presents the applied methodology of this work. This chapter's framework presents a dynamically integrated direct- and indirect flood risk model and is operationalized for the Rotterdam harbour area of The Netherlands. The framework consists of multiple steps and includes elements salient to integrative loss estimation. The methodology begins with a conventional risk assessment, using detailed flood hazard inundation maps to assess the direct losses in the harbour area, including a detailed differentiation of exposed assets of various industrial sectors. Second, these direct losses in both capital and labour can be translated into the loss in production per sector in a consistent manner, through the use of a Cobb-Douglas production function. In this regard, labour losses are of particular importance for large (low-probability) floods that may involve human victims. This production loss is used to calculate the imbalanced post-disaster economic situation. From this post-disaster situation, recovery and reconstruction are modelled up until time at which the region returns to its pre-disaster situation.

Whilst in Chapter 3 only a single-region flood event is coupled to a single-region economic model (ARIO-model), Chapter 5 extends this model through the use of the MRIA model. Since large-scale floods can affect several regions at the same time, which leads to highly correlated damages across European countries, the potential spatial effects of such floods are of great interest. For this reason, Chapter 5 explores how such large-scale floods in the largest river basin districts within Europe can be used to calculate the indirect losses. Through the use of direct damages as a measure for destroyed capital and the ratio of inundated area within a region as a proxy for employees unable to work, the model calculates the spatial indirect economic effects.

Such an approach, which results in a picture of both direct and indirect losses, lends itself to a much more holistic view of the potential consequences of floods within Europe.

8.3. DIRECT VERSUS INDIRECT ECONOMIC EFFECTS UNDER CURRENT AND FUTURE CONDITIONS

In the Flemish case-study (Chapter 2), risk related to direct economic effects is estimated for the coastal zone. Although it does not include indirect effects, the study already shows that the shipping industry contributes to almost 40 percent of the total (direct) flood risk. In consideration of the economic importance of such hubs, on both a regional and national level, the indirect economic effects could be of the same order of magnitude.

In Chapter 3, the indirect losses are also explicitly modelled, in relation to the direct losses for the area of Rotterdam. The results show that in terms of expected annual damage (EAD), direct losses remain more substantial in comparison to the indirect losses (approximately 50% larger), but in the case of extreme low-probability events, the indirect losses outweigh the direct losses. Moreover, different model parameters have different effects on loss estimates for the high-probability and low-probability floods. As outcomes of high-probability floods mainly influence the EAD, care should be taken in drawing conclusions about an ‘average’ effect of a specific model parameter. These conclusions imply that both the EAD, and its distribution in direct and indirect risk, must be considered to assess flood risk for a specific region and to make policy choices.

A multiregional approach, as shown in Chapters 4 to 6, establishes further aspects about indirect loss assessments. In Chapter 4, the results show that the cascading effects over the different regions may lead to substantial indirect losses and strong distributional effects between regions. The Rotterdam case in Chapter 4 clearly shows that many regions outside the affected area are indirectly affected by the natural

disaster. Some of the neighbouring regions benefit from the flood by increased reconstruction demand or by overtaking some of the production from the affected region.

Chapter 5 explores the pan-European effects due to flooding 5. This chapter considers economic effects from different flood scenarios in the fifty largest river basins in Europe, both for return periods now and in the future. The results indicate that the present aggregated indirect losses for the whole of EU+N vary between €1.9 and €3 billion per year, depending on the selected recovery path. These losses are less than half of the present direct losses (€8 billion per year). If the indirect losses are compared to the direct losses, the results show, that over all European regions, there is a median indirect/direct ratio of 0.27.

Under the SRES A1B scenario, through the use of an ensemble mean of twelve climate change models, the results show an increase in continent-wide indirect risk of approximately 40 percent compared to the baseline situation. This increase is 20% higher compared to the increase in EAD in the river basin districts considered in Chapter 5. This larger increase in indirect risk is due to the non-linear effect of an economic disruption: the effect of the disruption increases exponentially as a result of the cascading effects through the economy. As such, even a small increase in the disruption may result in a substantially higher indirect risk. Nonetheless, both EAD and indirect risk have a similar increasing/decreasing trend within Europe. There are, however, some observable outliers of interest. The entirety of Denmark, as well as some regions in France and Germany, show a decrease in EAD, but a slight increase in indirect risk. This result implies that due to trade effects, regions can still be affected more severely, even in the case that the flood risk in the region itself reduces in the future.

8.4. SOCIOECONOMIC DIMENSION OF FLOOD IMPACTS

In contrast to the other chapters of this dissertation, which considered the indirect effects on the level of industrial sectors, Chapter 7 explores the social dimension of indirect effects on a household level. In this chapter, hazard, exposure and social

vulnerability are combined to understand how the evaluation of flood risk management strategies can be improved at the household scale. The use of freely available household level data led to the identification of social vulnerability within each flood hazard zone and for the differences in social household composition between the flood zones of the Rotterdam urban area. The results indicate that the share of relatively lower class people in flood zones is twice as large as the number of relative higher class people. Moreover, the share of the population that is highly vulnerable to flooding is almost 20 percent in areas that are not embanked, in comparison to only six percent in embanked areas. This finding implies that in the areas most exposed to flooding, the most vulnerable people live. In a scenario of future risk, there is a slightly larger increase in the highly vulnerable population to be exposed to flooding (6% increase), compared to the low vulnerable population (2% increase). Additionally, the results show a clear spatial cluster between high and low social vulnerable groups, which indicates some degree of segregation in the study area.

If one assumes that a one-size-fits-all approach to conventional flood risk management (FRM) may lead to sub-optimal decisions, the results lead to both a heterogeneous composition of the population and a relative high share of a socially vulnerable population in flood-prone areas. In light of the increasing move towards integrated FRM, the inclusion of social vulnerability is an essential element to develop effective, equitable and acceptable risk management strategies.

8.5. THE EFFECTIVENESS OF DISASTER RISK REDUCTION MEASURES

Risk assessments employed in this thesis can be used to evaluate flood risk reducing measures. In Chapter 2, two spatial adaptation measures are assessed for the coastal area of Flanders by using a conventional flood risk assessment: compartmentalization and land-use zoning. The result of this study shows that compartmentalization (i.e. improvements of physical structures to prevent flooding) can substantially reduce flood risk up to 50% relative to the baseline situation. Land-use zoning and building restrictions, on the other hand, only result in a marginal decrease of flood risk (between 6% and 10%).

In Chapter 5, several adaptation measures are evaluated on a European-wide scale to assess their influence on flood risk. This chapter addresses both the effects of physical protection measures (e.g. increasing the strength of the dikes) and more production process-oriented adaptation measures. The results show that for all fifty flood events considered in the study, the improvement of the protection standards to 1/100 would result in a median reduction of both direct indirect risk of 54%. If standards are to be improved to 1/250, both risks would be reduced by as much as 89%. As proven in various chapters of this dissertation, slow recovery paths (linear and convex) are a large driver of indirect losses. Therefore, one interesting adaptation strategy is to improve the recovery process and to reduce the time to initiate this process. The results show that the indirect risk for the whole of Europe reduces by 22% and 35% in the case that a concave recovery path is assumed rather than a linear and a convex recovery. Finally, the removal of bottlenecks in the construction sector in the direct aftermath of the disaster (i.e. increasing its capacity) may reduce the indirect risk by as much as 40%.

As it becomes apparent from this dissertation's results, both the risk assessment itself and its use to measure the effectiveness of climate adaptation measures, direct and indirect losses are two complementary elements. Direct losses clearly indicate the magnitude of the flood within the affected area and can be used to measure the effects of adaptation measures to reduce the risk on a regional scale, or alternatively, the damage to buildings and other assets. Indirect losses, on the other hand, provide a much clearer image of the temporal and multiregional post-disaster effects. The assessment of the indirect losses is therefore of great value for climate adaptation measures, both structural and financial, which have a more interregional focus and effect.

Finally, this research recommends the inclusion of both physical and social vulnerability in risk assessment studies, which enables a comprehensive study of the feasibility of risk reduction strategies. Whereas the results of a physical vulnerability assessment may guide policy makers in the right direction of a strategy that effectively reduces flood risk, the addition of a social vulnerability assessment helps tailor such strategies to local differences in terms of the needs and capacities to implement strategies. First, these findings provide additional information for the detailed assessment of FRM strategies, which go beyond the traditional economic

cost-benefit analysis with respect to societal characteristics and spatial disaggregation. For instance, in the case that a large share of the inhabitants in a neighbourhood are elderly, one may move from individual mitigation measures to implement more structural flood protection infrastructure. Second, due to this large heterogeneity in the population and the relatively large share of highly vulnerable and low-income households, a successful risk insurance policy requires a localized approach. Although a broad flood insurance coverage is often seen as desirable for a households' capacity to recover from flood events, the affordability of insurance proves to be problematic among more (financial) vulnerable households. To overcome this affordability issue, this research suggests subsidy and insurance voucher programs. For an optimal and efficient implementation of such programs, the social vulnerable index proves to be a suitable supporting tool.

8.6. AN OUTLOOK TO FUTURE RESEARCH

As made apparent in the previous sections, this dissertation has explored and extended the current state-of-the-art methodologies in several ways to improve their use for the economic modelling of flood risk. Nonetheless, there are still several ways that the methodologies could be further improved and extended. For example, all the methodologies presented in this dissertation assume a return to the pre-disaster production levels and ultimately pre-disaster production capacities. Such a comeback, however, may not necessarily be targeted or even possible in all real world post-disaster situations. Future research may therefore explore other recovery trajectories. Besides, there remains much unknown about the duration of the recovery as well as the recovery process. This dissertation's methodology (but also the methods not covered in this dissertation) requires assumptions to model the recovery period. For this reason, there is especially the need for more empirical research on how businesses recover from floods to improve the reliability of the results used for risk reduction policies.

Secondly, one of the current focus points for policy makers is the vulnerability of critical infrastructure to natural disasters. Infrastructure is the backbone of economic growth and social cohesion. The disruption of (critical) infrastructure, as a result

of natural hazards, may be estimated through productivity losses and increased cost of production, which are set in motion by the substitution of more efficient and competitive supplies with lesser efficient supplies. For impact assessments, it is essential to outline the spatial extent of regions physically unaffected by the extreme event(s) that are disrupted as a result of damaged infrastructure. The economic impacts caused by disrupted infrastructure, although caused by the same extreme event as the physically damaged area, may only to a small extent be correlated with productive capital damage. Instead, the impact should be viewed as additional. The economic modelling frameworks in this dissertation can provide a framework to understand the effects of the failure of critical infrastructure that results from large-scale flood events.

Thirdly, there is an increase in focus to model the economic effects of extreme weather events, such as extreme rainfall, wind and hail. In the Netherlands, for instance, wind and hail storms are the most costly events for the insurance sector and have a much larger probability of occurrence in comparison to large-scale river or coastal flooding. Moreover, in relation to the failure of critical infrastructures, the modelling frameworks that this dissertation presents serve as a good starting point to develop methods to assess the economic consequences of extreme weather events.

Household migration is another field of study that is still in its infancy regarding the incorporation in disaster impact analysis. Both IO and CGE models have limitations to represent household migration under disaster risk. More specifically, individual risk judgements and public concern are likely formed and shaped through interactions between individual agents with heterogeneous beliefs. Such interaction effects could possibly lead to multiple equilibria that are not easily captured within IO and CGE models. Combining IO and CGE models with elements from agent based models (ABMs) could potentially address such limitations. Researchers develop ABMs to study microeconomic phenomena, such as the impact of flood risk on migration decisions (Böhringer & Rutherford, 2008). However, the introduction of additional assumptions and extra layers of complexity can render ABMs vulnerable to black box criticism, as only a small number of practitioners are able to use the models in a meaningful way. In comparison, the use of tractable models such as IO and CGEs are easier to learn. Rather than discarding the models that currently in use, step-wise

improvement may be applied to combine existing models with ABMs, as the rigorous structure of IO and CGE models set limits on outcomes from the ABM, whereas the ABM adds realistic behavioural features to the IO and CGEs.